Test of Prototype Power Leads HINS_CH_LDHTS_01

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Introduction

The concept for power leads to energize superconducting solenoids in the CH section of the HINS linac includes an upper resistive section, designed and built by Fermilab, electrically connected to a lower HTS section obtained from an industrial supplier. The resistive section is cooled by liquid nitrogen, which maintains the HTS warm end temperature at 82K. The bottom of the HTS section is submersed in liquid helium, and is spliced to a section of low temperature superconductor (LTS) for connection to leads on the solenoid. In 2006, based upon previous HTS power leads projects in Technical Division, a requirements specification document was developed [1] and requests for proposals were sent out. Early in 2007 two pairs of prototype HTS leads were procured from commercial vendors for evaluation as potential components for the CH section cryostatted solenoid assemblies. In this report, the assembly and test of one pair of Ag-BSSCO(2223) HTS evaluation leads, built by Cryomagnetics, Inc., is described. The cold test took place in the IB1 stand 3 dewar on November 7, 2007.

Device and Apparatus

Resistive Section Design, History, and Construction

The upper resistive section design uses copper conductor of an appropriate cross section (at a fixed length) to carry the desired current – up to 300 A – with heat conduction adjusted to maintain the power lead flags close to room temperature. The design assumes a lead made from RRR~80 copper and length 0.2m, which results in optimized cross section of 17.4 mm^2. Electrically insulated liquid nitrogen heat exchangers surround the copper conductors near the connection to the HTS section of the lead, and a sufficient flow of boiling nitrogen maintains the temperature of this point at 82K. In the nominal design, **nitrogen flows in series** to cool both leads.

Two versions of the upper copper resistive section have previously been built with the liquid nitrogen heat exchange system, and were tested using a small stand-alone vacuum vessel for insulation and by adapting the stand 3 power and readout systems. The first of these tests used a number of parallel wires to achieve the desired cross section, and was tested as a device named "pdrt_ldcu_p1" ("pdrt" represents the "proton driver room temperature section", "ldcu" refers to "leads of copper", "p1" indicates "prototype 1"); this device operated successfully on June 1, 2006 (some test notes exist, but a test report has not been released). The second device was named "hins_ch_ldcu_02", reflecting the association with the CH section of the HINS linac, dropping the prototype distinction but identifying it as the second copper lead device. This second device used copper braid to achieve a more flexible assembly (for cryogenic shrinkage), but this design failed to operate with a stable temperature profile at 300A – the upper section temperatures continued to rise in a run-away condition.

The resistive section design for HINS_CH_LDHTS_01 was made by soldering together in parallel six gauge 10 stranded wire conductors to provide the necessary copper cross section, yet maintain flexibility, in each lead.

Copper/HTS and LTS Joints

The Cryomagnetics lead uses an internal Indium solder connection to the HTS material, and therefore requires a low-temperature external solder joint to the resistive section. Therefore we also made this external copper/HTS lead connection with Indium solder, and it was specifically instrumented with voltage taps to determine the resistance of the joint. The splice between leads was made by soldering the LTS strand ends together for a length of 5 cm using 60%Pb-40%Sn solder.

Instrumentation and Test Configuration

The instrumentation list was developed to satisfy the requirements of the test program, which are described in the next section. This list consisted of test stand sensors within the dewar (Cernox RTDs, Liquid Level probes) and external to it (Nitrogen flow and differential pressure; helium pressure), and as shown in Figure 1 on the power leads themselves (Platinum RTDs and Voltage Taps). A photograph of the final lead assembly with a mechanical dimension map is also shown in Figure 1. The voltage taps V3 and V4 were provided already attached by the manufacturer: there were two taps in each location – one "primary" and one "redundant".

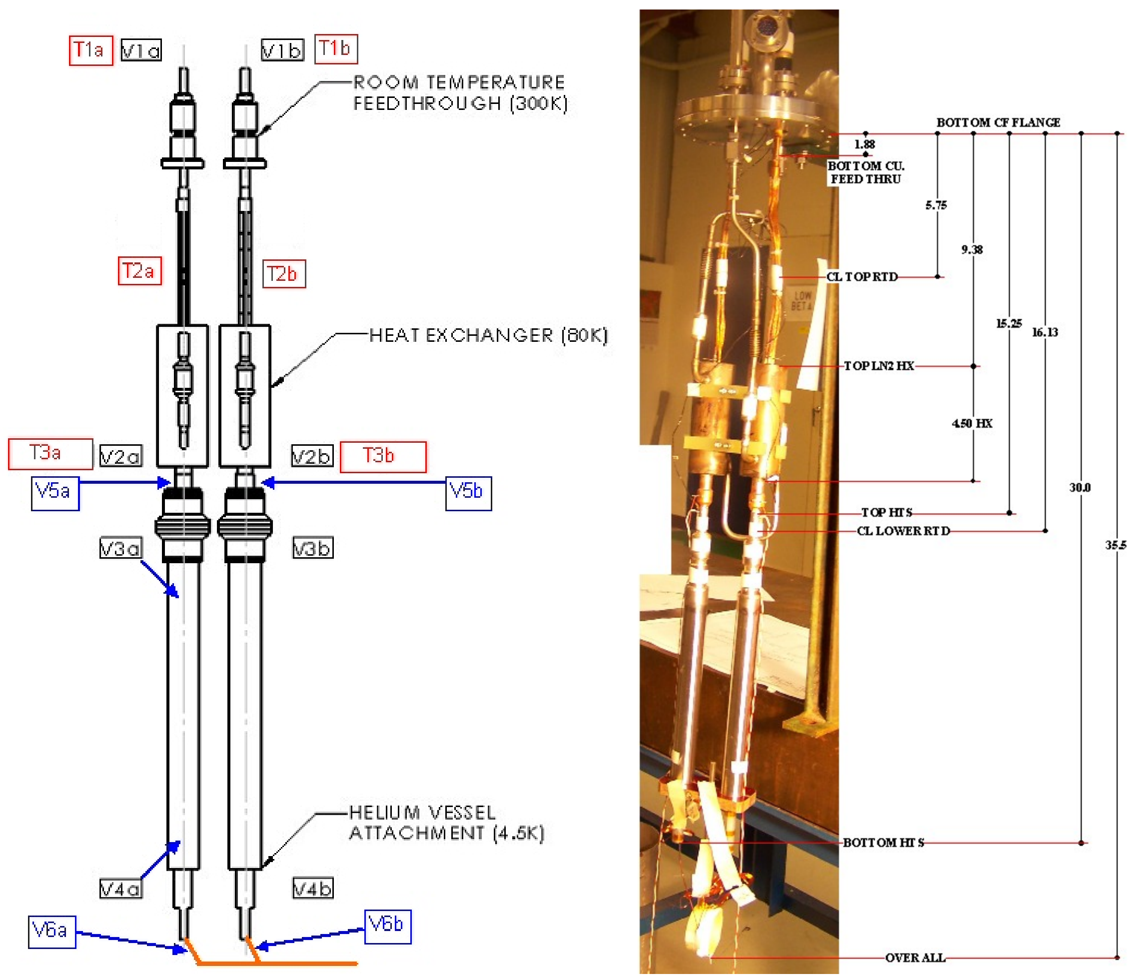

Figure 1. Leads with Voltage Tap and Temperature Sensor Instrumentation, and photo of Cryomagnetics leads assembly with dimensions prior to cold test; dimensions are shown in inches.

Figure 2 shows the power and LN2 flow schematic for this test. Lead A was connected to the Positive power supply terminal, and Lead B was connected to the Negative terminal. Liquid Nitrogen was supplied to the Negative lead (B). N2 flow was controlled with a rotameter through which the warm gas flowed, and measured using an existing flow transmitter, FT519 in the IFIX database (from which flow rates are listed here). During the actual test, it was realized that the labels on some temperature sensors were incorrect: T2a and T2b were swapped, and T3a and T3b were swapped – this was confirmed after the test using a heat gun to check individual RTDs. A 12" level probe was positioned with the top end of the probe 6" from the bottom of the HTS leads.

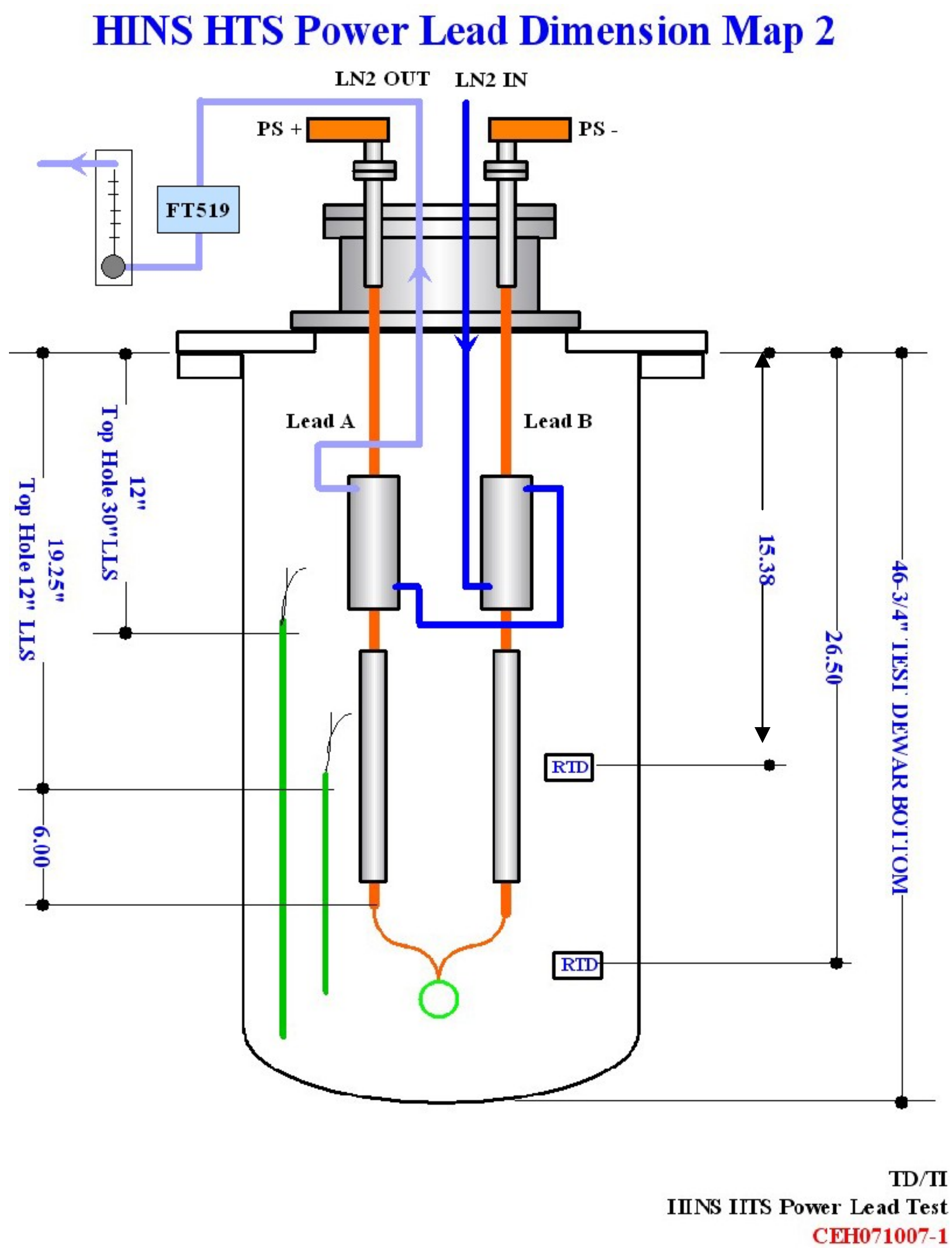

Figure 2. Power, flow, and liquid level schematic for HINS_CH_LDHTS_01 test. The dewar vent location (not shown) which is relevant to helium temperature gradient and convection, was at about the same level as the top Cx RTD, 15.25" below the flange.

Cold Test Procedure and Test Results

Elements of the cold test plan were defined by the Requirements Specifications document [1]. The relevant elements with a brief description of the main requirements (refer to sections in [1] for more details) are as follows:

Integrity of Electrical Insulation: withstand 1000 V to ground – (Sec. 3.3)
Heat Load to 4.5 K bath in standby (no current): <0.1Watt per lead – (Sec. 3.6)
Resistive section cooling flow rate in standby: <0.5 g/s per lead – (Sec. 3.7)
Heat Load to 4.5 K bath at 300A: <0.1Watt per lead – (Sec. 3.4)
HTS-LTS Joint Resistance at 300A: $<5 \times 10^{-7}\ \Omega$ – (Sec. 3.4)
Resistive section cooling flow rate at 300 A: <0.5 g/s per lead at 80K – (Sec. 3.5)
HTS warm end temperature at 300A: <350K – (Sec. 3.10)
Pressure drop in 80 K cooling circuit: <50mbar at required flow – (Sec. 3.8)
Resistive section temperature at decreased flow rates: stable at 5% below optimal flow at nominal temperature - (Sec. 3.5)
Measure HTS temperature margin: must be stable at 82K – (Sec. 3.11)
Loss of coolant survival: no degradation at 300A @1mV threshold – (Sec. 3.12)

The detailed cold test chronology is included as Appendix I. Figure 3 gives an overview of the lead temperatures, LN2 flow, current and liquid level during the entire test. A summary of the "equilibrium" thermal conditions is shown in Table 1.

Thermal Measurements

We first established the minimum required LN2 flow to maintain the warm end of the HTS section (bottom end of the resistive section) at 82K at 0A. The actual sensor (and voltage tap) locations at the joint are shown in Figure 4. This was done with the helium liquid level set to 7" (17.5 cm), which places the level at the middle of the 5cm long HTS/LTS flag. Note that the helium supply valve to stand 3 was set in "Bottom Fill" mode for the entire test. Because of the effects of helium convection discussed below, there is some uncertainty about the actual temperatures and actual required LN2 flow (they are underestimated). The pressure drop in the LN2 circuit fluctuated a lot, and varied considerably at constant flow rate, but apparently depending upon the helium conditions (such as liquid level). At least 1.13 g/s was required to maintain 82K on the positive lead (outgoing LN2 flow), which always showed the highest temperature.

We attempted to make measurements of heat loads to the bath by looking at helium boil-off rates. This is a very difficult measurement to make at the required level, in the presence of background heat loads (measured in the past) of about 2.5 Watts. On several occasions we set the liquid level to the mid-point of the HTS "flag" and let the level drop somewhat below the flag, in order to measure the rate with and without the contribution from the leads. However, boil-off rates varied considerably: we later realized that there were a number of problems in the design and execution of this test. First, when the liquid level set point was changed to a low value, the supply valve did not always remain fully closed until the new liquid level was reached – so, some helium was supplied. Second, convection within the dewar must contribute substantially to the heat exchange processes, and opening or closing the dewar vent makes a big difference in the boil-off rates. Third, it was not realized that Bottom Fill mode could make significant contributions to convection.

The helium contributed to cooling of the resistive section so it was not, strictly speaking, a clean test of the "conduction cooled" leads. This became evident when the resistive section temperatures became quite asymmetric, with temperatures sometimes below the temperature of liquid nitrogen at the supply pressure. The helium can affect not only the actual lead temperatures, but because the RTD sensors are exposed to helium vapor they may indicate a temperature below that of the lead in which they are in fairly good contact.

The resistive sections performed well in power testing at 300A. The flag temperatures were about 280K in standby mode, and rose to a stable temperature of about 305K at 300A. Temperatures in the middle of the resistive section were also stable but sensitive to LN2 flow. The required minimum flow at 300A was 1.37g/s. Again, one can see during the attempted 300A boil-off test that temperature conditions changed immediately after the bottom fill helium supply was turned off.

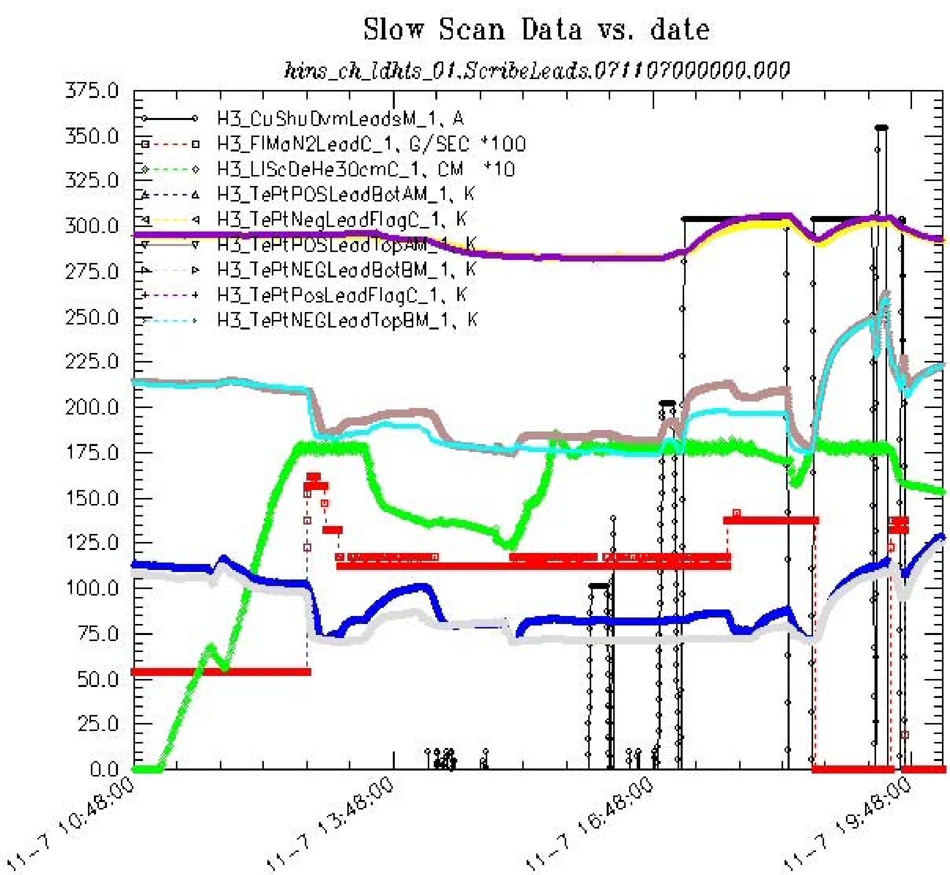

Figure 3. Overview of LN2 flow, liquid level, current, and resistive section (flag, top, bottom) lead temperatures during the entire cold test (Note: swapped labels have been corrected here).

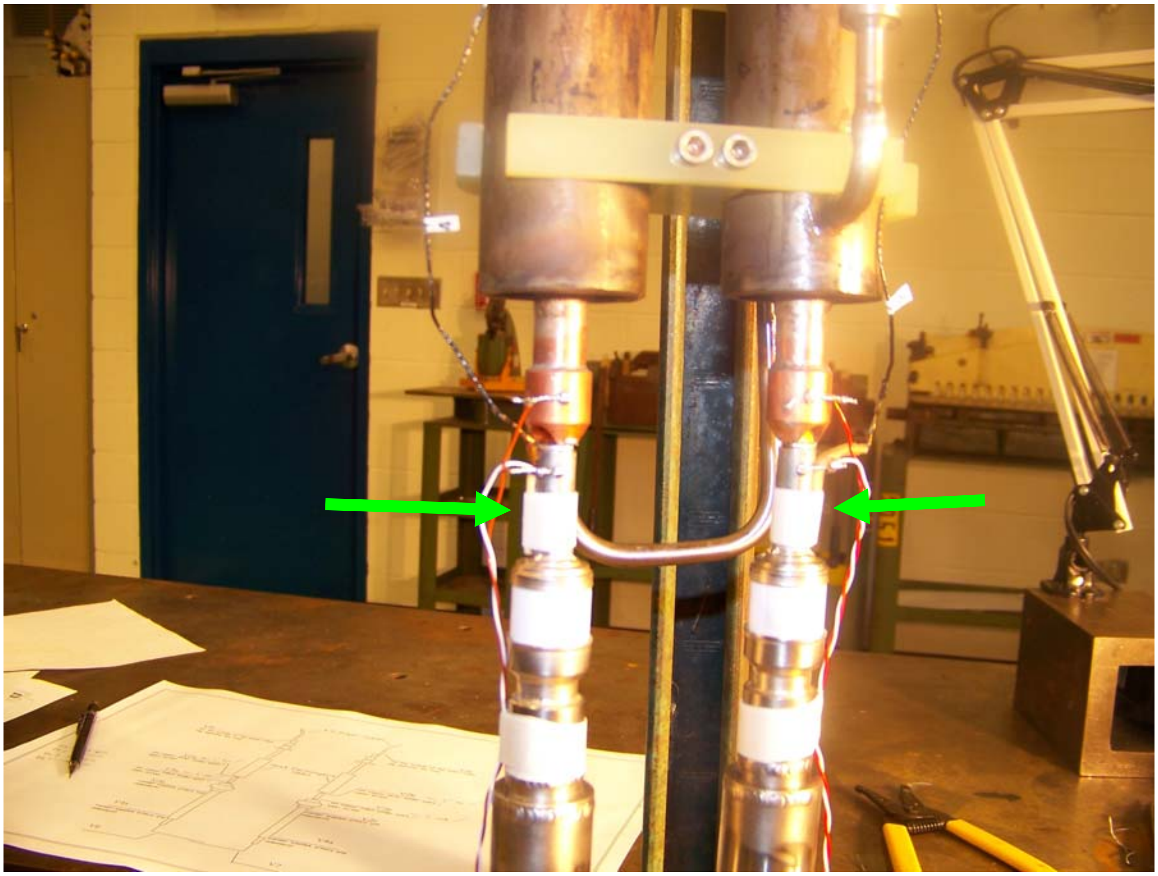

Figure 4. Arrows show Pt temperature sensor locations below the LN2 heat exchangers at the bottom copper/upper hts section of the leads. Voltage taps (red, white wires) span the indium solder joints.

Table 1. LN2 flow and "equilibrium" temperature conditions at HTS warm end

Time line / action	LN2 mass flow [g/s]	Differential Pressure [psia]	Neg. lead temp. T3b [K]	Pos. lead temp. T3a [K]
Initial cooldown	0.54	.17	98	102
Raise flow	1.6	.91	72	72
Reduce flow	1.32	.71	71	75
Reduce flow	1.13	.44	71	82
Close He vent (blockage)	1.13	.58	80.5	80.5
Refill dewar w/ He	1.13	.30	71	82
Ramps to 100 A, 200 A and 300 A for resistance measurements.				
Hold @ 300A for 32 min.	1.13	.30	72.3	86.4

Hold @ 300 A, raised flow	1.37	.45	71.8	76.5
Ramp down and back up to 300 A to perform loss of lead flow test				
Hold @ 300 A for 40 mins	0	0	107	112.5
Ramp to 350 A	0	Quench detected, Neg. Lead		
Re-establish lead flow, helium supply depleted, ramp to 300 A and hold a couple of min.				
@ 300 A, not in LHe	1.37	.55	94	108.5

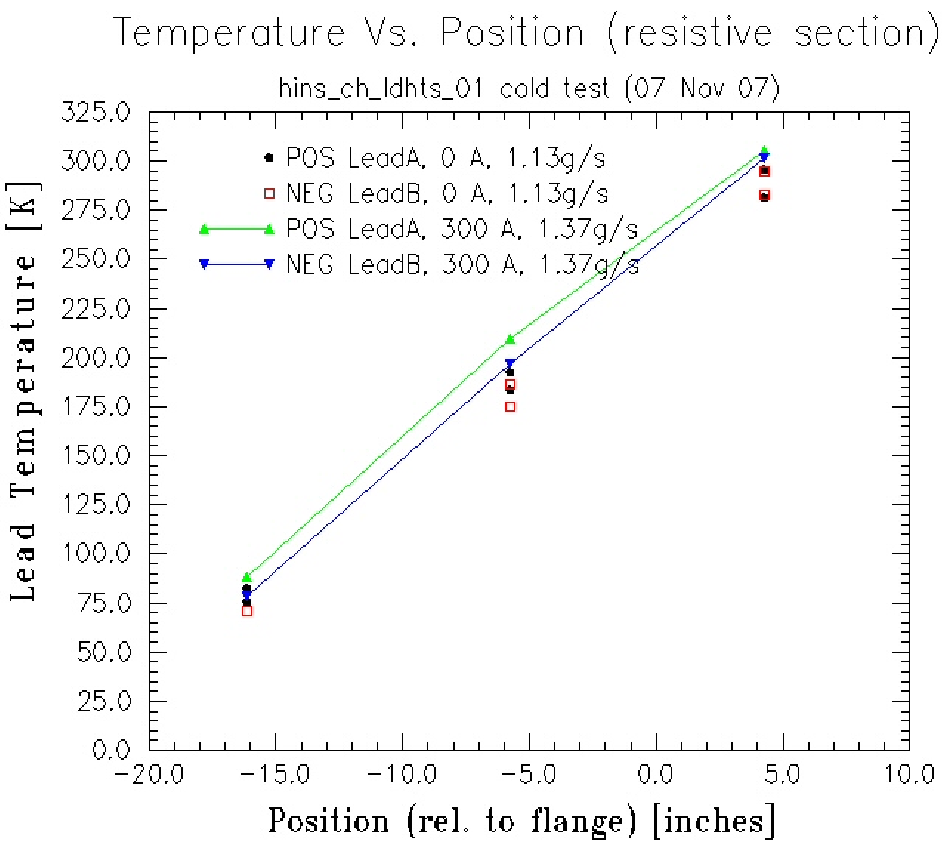

Figure 5. Resistive section temperature profile, at the minimum required flow condition in standby and when powered at 300A. The standby condition points show the level of temperature variability due to helium cooling conditions during the test.

Voltage Measurements

A summary of the joint resistance values is shown in Table 2. Voltages across the lead segments were measured with a HP 3458 DVM, integrating over a power line cycle, after amplification with the “MTF_Isoamp” fully programmable vme-based amplifiers and multiplexed through a standard HP 1351 FET multiplexer. All of the “resistive” voltage tap segments showed clear linear behavior with current and were easily fit to obtain the resistances. The LTS splice segment was consistent with no resistance.

Table 2. Resistances of the Current Lead Segments

Segment	Location	Gain Used	R(Pos. Lead A) [μΩ]	R(Neg. Lead B) [μΩ]
V1V3	Copper Section	10	150.8 ± 0.35	149.4 ± 0.25
V2V5 (82K)	Indium Solder Joint	200	1.098 ± 0.001	0.856 ± 0.003
V2V5 (110K)	Indium Solder Joint	200	1.956 ± 0.020	2.064 ± 0.014
V3V4	Primary hts+joint	10	0.407 ± 0.004	0.449 ± 0.017
V3RV4R	Redundant hts	10	0.0639 ± 0.0028	0.0697 ± 0.0017
V4V6	HTS/LTS Joint	10	0.409 ± 0.002	0.449 ± 0.003
VSplice	LTS Splice	1000	-0.104 ± 0.004	

Figure 5 shows the trend of HTS voltages with current (thermal EMFs introduce offsets of several mV). The "primary" and "redundant" taps across the HTS section behaved differently: the primary taps were resistive, while the redundant taps were not, so it appears that the former must include at least one resistive joint (copper or LTS).

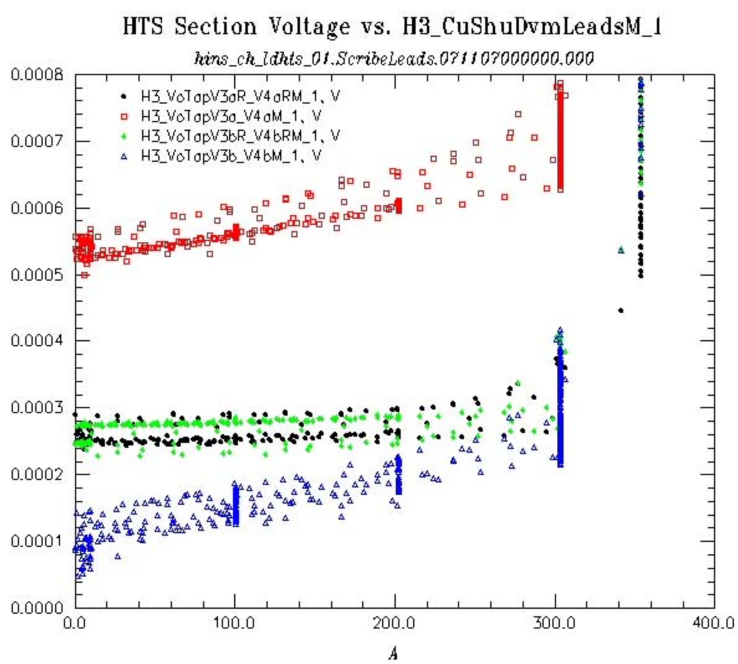

Figure 5. HTS section voltages versus current: primary tap segments look resistive, while redundant tap segments do not (until quench at 350 A, where both segments agree well).

Both primary and redundant segments became resistive during the LN2 coolant-loss quench event. Figure 6 shows the time dependence of the primary tap voltages during powering: the voltages respond linearly to current due to internal joint resistance, and non-linearly due to temperature rise of the HTS material when N2 flow is reduced to zero – especially at 350A leading to the HTS quench.

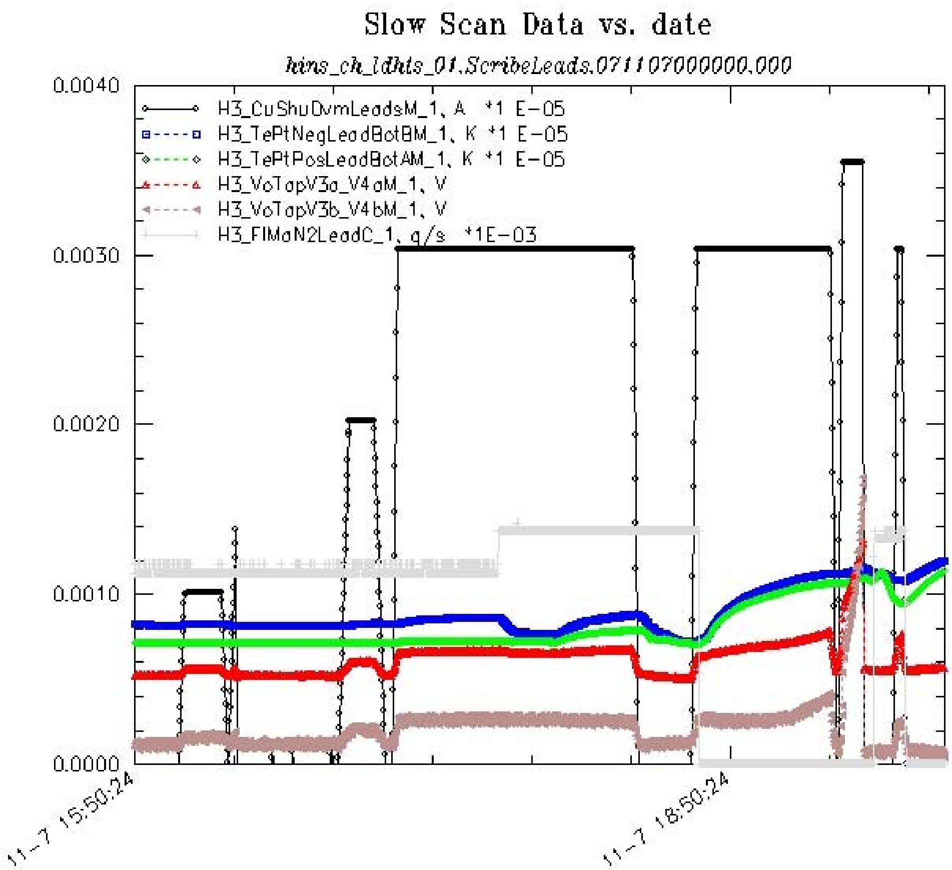

Figure 6. Time dependence of Current, LN2 flow, HTS warm end temperatures, and HTS voltages during the power testing.

In Figure 7, the HTS voltage is shown as a function of the temperature at the HTS section warm end. The lower horizontal lines represent thermal EMFs during periods of un-powered operation. Ramps at different temperatures appear as (near) vertical lines due to the internal joint resistance. As the temperatures rises at high current, the voltages follow a rising trajectory – rising slowly and still very stable at 300 A, and rapidly rising to quench at 350 A. The negative lead quenched, even though it was at lower temperature, which may indicate (if temperature readings are accurate) that there is some variation in the current margin of the leads.

Following the quench event, LN2 cooling flow was re-established, and the leads were again powered to 300 A. At this point, the helium supply dewar was empty, and the stand 3 helium level began to fall. Nevertheless, even at elevated temperatures, the leads were able to operate at 300 A for several minutes without any problems, thus revealing no evidence of degradation.

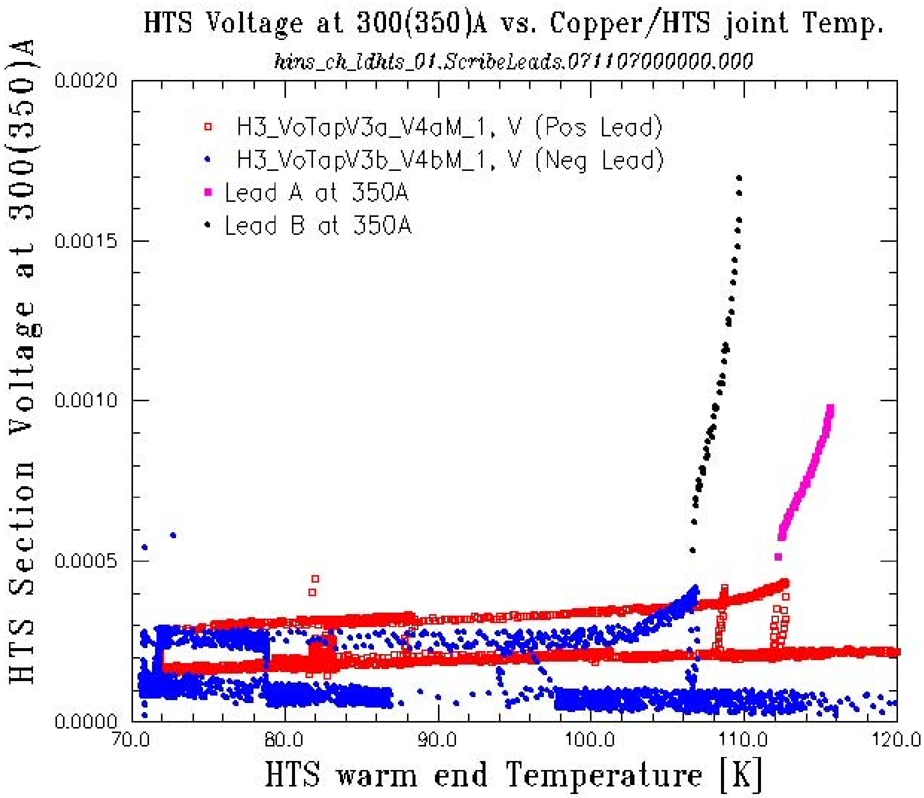

Figure 7. Voltage across the HTS section when powered at 300 A and 350 A, as a function of the temperature at the warm end of the lead.

Conclusions

The Cryomagnetics HTS leads performed well in this test, and met specifications. They operated without any voltage growth for long periods at 300 A with the minimum required LN2 cooling flow maintaining the warm end temperature at about 82K. During the coolant loss test, even as the temperatures rose significantly above the required minimum 82K level to about 110K, the voltage growth was slow and the lead performance suggested plenty of operating margin. We were able to induce a quench by raising the current to 350 A in the no-flow condition; subsequently, the leads performed successfully without signs of degradation.

The performance of the upper resistive section was also successful, from the standpoint of the flag temperatures being fairly stable and insensitive to the LN2 cooling conditions. The measured minimum required LN2 flow is underestimated in this test, due to additional cooling that occurred from helium convection within the stand 3 dewar; yet the measured value (1.4 g/s at 300 A) is greater than the prediction (1.0 g/s).

References

[1] S. Feher, T. Page, Fermilab Specification FNAL#5500-ES-371036-01, “300A Current Leads Using High Temperature Superconductor for the HINS Superconducting Solenoid Magnets”, 06 June, 2006

Appendix I. HINS_CH_LDHTS_01 Cold Test Chronology on 11/7/07

07:12 Start Transfer of liquid Helium to stand 3 dewar
Kepko PS is turned on (toggling +/- 0.5A)
08:40 Kepko PS is turned off – voltages are all quite small
08:48 Start 0.59g/s LN2 flow to lead heat exchangers
11:40 First helium dewar empty, change to second 500 liter dewar
11:55 Adjust LN2 shield temperature from 120K to 82K
12:42 Helium liquid level reaches 7” (=17.7cm = middle of 2” long LTS “flag”)
LN2 mass flow to leads is 45 scfh (rotameter) = 0.54 g/s (flow transmitter)
temperatures at copper Bottom location read 102K(-lead) and 98K(+lead)
this is strange because the LN2 flow is thought to be IN(-), OUT(+)
One possibility is that thermometry labels are not correct → check after test
Another point is that helium gas contributes, and position of dewar vent may
be important → check after test
12:50 Raise leads LN2 mass flow to 103 scfh = 1.60 g/s
Allow Bottom temperatures to stabilize at 72K(-) and 72K(+)
13:00 Reduce leads LN2 mass flow to 90 scfh = 1.32 g/s
Bottom temperatures stabilize at 75K(-) and 71K(+)
13:10 Reduce leads LN2 mass flow to 80 scfh = 1.13 g/s
Bottom temperatures stabilize at 82K(-) and 71K(+)
82K is the nominal max HTS temperature, so hold at this flow for
Initial heat load and power testing;
dP = 0.56 psid across the leads LN2 circuit
Cold Electrical Hipot is successful
Electrical Techs connect power lead flags and reattach Pt RTDs to the flags
13:28 Start “standby mode” heat load measurement
Change set point of helium LL from 7” to 4.5”, watch dLL/dt
NOTE: Bottom and Top(mid copper section) temperatures start to rise !
13:40 At 5.6” level we set LL to 7” again, but Helium transfer line is blocked !
NOTE: rate of dLL/dt decreases dramatically at this point – why??
(LL is also very steady – as if it isn’t being disturbed –
14:05 Stand 3 Dewar vent closed while trying to clear blockage
Lead bottom (and top) temperatures start to fall !
dP was noisy, then suddenly became calm at 0.6 psid
Power and quench system tests performed (up to 10A)
FPGA current signal offset problem (labview readout only) is debugged
15:00 Transfer line blockage cleared (it was on the supply dewar side of control valve)
Both Lead Bottom temperatures have come to nice equilibrium at 80.5K
LN2 lead mass flow has been constant at 1.13g/s; dP constant at 0.6psid
15:05 Start refill to 7” level
Bottom lead temperatures both fall to 72K, then diverge to
82K(-) and 71K(+)
15:10 dP suddenly drops from 0.58 to 0.30 psid – LN2 flow is constant
PS system fiddling… install new Matlab analysis exe on pxi-cont-04
16:04 Ramp to 100A at 1A/s – hold for 12 min to look at voltages and QD noise levels
16:19 Ramp to 200A at 1A/s – trip on Whole coil signal at 50mV (dominated by Vcu)

Electrical techs add a “WCinternal” (V5a_V5b) signal to QC
WC threshold raised (ran at 80mV)

16:50 Ramp to 200A at 1A/s – hold for 7 min to allow temperatures to stabilize
17:08 Ramp to 300A at 3A/s – hold for 32 min to watch temperatures
(QD “whole coil” threshold is 200mV)
Bottom (-) lead temperature reached 86.4K,
Flag temperatures still rising slowly –
17:40 Still holding at 300A, we raise lead LN2 flow from 80 to 90 scfh = 1.37g/s
Tbottom (-) quickly falls to 77K (then to 75K more slowly);
some 1.5K oscillations are visible in the bottom(-) temperature
NOTE: that the (positive lead)voltage V2a_V5a also dropped with this temperature change (but not V2b_V5b), indicating that
either the temperature or voltage labels must be incorrect
15:57 Attempt another heat load (boil-off rate) measurement at 300A
Change LHe level set point from 7” to 6”
Note: bottom lead temperatures start rising again as soon as liquid level starts to fall
I note that the “Half Coil” (HTS^+ - HTS^-) QD signal averaging ~ +0.5mV
With a noise level of about +/- 0.2 mV
18:19 We are surprised how slowly the liquid level is changing: -0.3” in 20 minutes
So reset the LL to 7” (which first introduces some warm gas from the transfer line); ramp down to 0A
18:38 Ramp to 300A at 3A/s to perform Coolant Loss Test
18:40 Lead LN2 mass flow shut off
19:20 Temperatures and Voltages are still slowly rising; pretty stable after 40min!
Tbot(-) at 120K but still no quench; we decide to try higher current
19:23 Ramp to 350A at 4A/s (Lead LN2 flow is still zero)
19:30 “Quench” detected by Half Coil circuit at -1mV, PS ramp down
V(-HTS lead) exceeds V(+HTS lead) by 1mV
NOTE: Half coil QD signal says 3.5mV ?? (not 1mV) → study this
19:33 Re-establish Lead LN2 mass flow of 90 scfh = 1.37g/s
Helium supply is depleted !
19:40 Ramp to 300A at 4A/s – hold a couple minutes without quench
Tbot(-) about 108K, Tbot(+) about 93K)
He LL = 6.1” – a sharp change (fast to slow) in the rate of LL fall at this point ! ?
19:45 Test Ended

Post-test measurements 11/8-9
dP cross-comparison to visual gauge:
N2 gas Flow = 1.176 g/s, dP(PDT511_3)=0.657psid
Gauge=22”H2O (+/-3%) / 27.7 “H2O/psid = 0.794 psid
Check Pt thermometry labels w/ heat gun:
Pt sensors on Flag positions are correct; Pt sensors on leads are REVERSED (A←→B)